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Illusory depth perception of oblique lines produced by overlaid vertical disparity

Hiroyuki Ito *

Department of Visual Communication Design, Kyushu University, 4-9-1, Shiobaru, Minami-ku, Fukuoka-shi 815-8540, Japan

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Abstract

Our visual system matches images from both eyes to establish a single view and stereo depth even when they contain a certain amount of vertical disparity. This paper demonstrates a new stereo effect showing an aspect of vertical disparity processing. When oblique lines without disparity are overlaid with sparse random dots with vertical disparity, the lines look closer or farther in depth. The characteristics of this stereo illusion were experimentally investigated. The results showed that the sign of the perceived depth of the oblique lines depended on the combination of the line orientation and the vertical disparity sign, and that the amount of perceived depth became larger as the line orientation became more horizontal. The depth illusion robustly existed even under conditions that ruled out eye movements (i.e., vertical vergence and cyclovergence) by local-parallel or brief presentations of the stereo figures. This phenomenon suggests that the visual system locally measures vertical disparity and is not simply tolerating a small amount of vertical disparity. Stereo capture of vertical disparity and horizontal matching after vertical image shifts were proposed as possible explanations for the depth illusion.

1. Introduction

Our visual system matches images from both eyes to establish a single view and stereo depth (Howard & Rogers, 1995; Julesz, 1971; Wheatstone, 1838). Horizontal disparities between the two eyes are used as a depth cue. Although the stereo system can match images containing small vertical disparities (Duwaer & van den Brink, 1981; Nielsen & Poggio, 1984; Stevenson & Schor, 1997), the contribution of vertical disparity to stereo depth was considered as small (Cumming, Johnston, & Parker, 1991; Westheimer, 1984). Recently, though, vertical disparity has been proved to effectively contribute to surface-slant perception when a vertical disparity gradient is presented with a reference plane (Howard & Kaneko, 1994; van Ee & Erkelens, 1995).

This paper describes a stereo effect that shows a new aspect of vertical disparity processing and proposes possible explanations for the effect. Fig. 1 shows the basic effect and a schematic illustration of the stereo stimuli tested here. In this figure and throughout this paper, when a right-eye image is higher in the visual field than the corresponding left-eye image, the vertical disparity sign is defined as positive. On the other hand, when a left-eye image is higher in the visual field than the corresponding right-eye image, the vertical disparity sign is defined as negative. That is, the dots in the second row in Fig. 1 have positive (negative) vertical disparity in the lower (upper) part. When oblique lines without disparity and sparse random dots with vertical disparity are presented simultaneously and fused binocularly, the oblique lines look closer or farther in depth whereas the dots do not. When the dots are observed alone, they

* Tel./fax: +81 92 553 4496.
E-mail address: ito@design.kyushu-u.ac.jp

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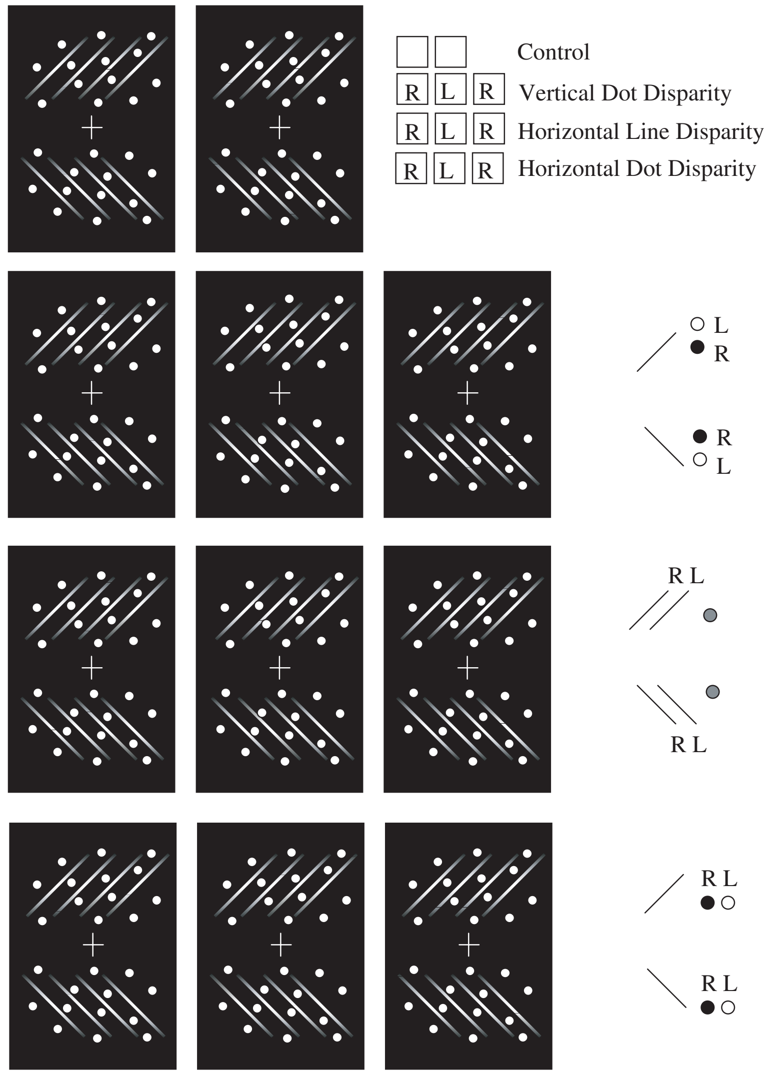

Fig. 1. The free-view stereograms of the present effect. The first row is a control without disparity, looking flat. For the second, third, and fourth rows, a "crossed-eye" person should use left and center panels and an "uncrossed-eye" person should use center and right panels for stereo viewing. The second row shows the present effect. The lines without disparity look closer than the cross and the dots and the depth is similar to the third row that includes real horizontal disparity of the lines. The fourth row shows that the horizontal dot disparity does not produce the present effect.

do not produce a strong impression of depth (if any). However, the effect of vertical dot disparity appears as illusory depth in the lines. The depth impression of the present effect (the second row in Fig. 1) is quite similar to that of lines with horizontal disparity overlapped with dots without disparity (the third row in Fig. 1). When the dots have a horizontal (not vertical) disparity, the dots are seen in depth, yet they do not induce depth in the lines (the fourth row in Fig. 1). Ito (2000) presented oblique lines without disparity and dots with disparity in the same orientation as that of the lines. The oblique lines appeared to bend in depth according to the gradient of the oblique dot disparity. An effect of vertical disparity of the dots on the perceived depth of oblique lines has also been reported in a Pulfrich display (Ito, 2003). Moving oblique lines were presented under Pulfrich conditions, where the perceived motion direction of the lines was controlled by moving random dots. When the dots moved vertically, the Pulfrich depth of the oblique lines disappeared.

As for a possible explanation of the present effect (the second row in Fig. 1), at first, I conjectured that eye movements produced the phenomenon (vergence hypothesis). Vertical disparity sometimes indicates a misalignment of the eyes in a vertical dimension. In this case, vertical vergence may occur to compensate for the vertical misalignment of the both-eye images on the retina. When vertical vergence occurs to compensate for the vertical disparity of the dots as shown in Fig. 2, though, it may introduce a new vertical disparity for the oblique lines as a result. However, the disparity direction of the oblique lines is ambiguous (the aperture problem in stereopsis Morgan & Castet, 1997). That is, the induced disparity may include a horizontal disparity

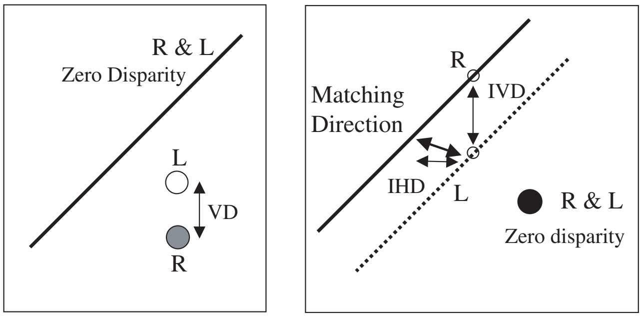

Fig. 2. The "vergence hypothesis". The left panel shows the original configuration of the stimulus. Here the dot has negative vertical disparity. The right panel shows the vergence hypothesis. Vertical vergence shifts the whole image to cancel the vertical dot disparity. As a result, newly induce vertical disparity (IVD in the figure) was introduced for the oblique lines. The stereo matching direction may lie between the horizontal and the nearest neighbor direction. The stereo matching may include an induced horizontal disparity component (IHD).

component because the matching direction may be oblique, not vertical (van Ee & Schor, 2000). Therefore, the vertical vergence could have induced the lines' depth.

Cyclovergence could also have produced disparity for the oblique lines. The global rotation in the opposite directions for both-eye images could have produced vertical or horizontal disparity in both signs that depend on the direction of eye rotation and the retinal position of the image. van Ee and van Dam (2003) showed that the stereo system did not use eye-rotation information for modifying a stereo matching direction even if cyclovergence occurs. That is, the stereo matching process only depends on a retinal coordinate without compensation for eye rotation. Following this, in addition to the induced horizontal disparity, the induced vertical disparity may have produced a horizontal disparity component through oblique stereo matching.

To carefully test the vergence hypothesis, two techniques were incorporated. One was a parallel presentation of test images as described in Section 2. Each quadrant of the visual field included a vertical disparity of a different sign (positive or negative). As vertical vergence or cyclovergence produces a global image shift or rotation, respectively, it is impossible for an eye to shift or rotate the retinal images locally in opposite directions at the same time. Thus, local independency of the effect would deny the vergence hypothesis. The other technique used for testing the vergence hypothesis was brief presentation of the test images, with durations too short to permit eye movements (e.g., 67 ms in Experiments 1 & 2).

2. Demonstration

Two stereograms were produced, each of which included four stimulus patches and a central fixation cross as shown in Fig. 3a and b. In the first stereogram (Fig. 3a), top-left and bottom-right patches included positive vertical disparity of the dots, while the top-right and bottom-left patches included negative disparity. This configuration was balanced in the disparity direction, i.e., effective to prevent a vertical vergence from occurring. If a vertical vergence occurred, all of the lines in the four patches should be seen at the same depth (closer or farther) at the same time, because the line orientation was the same for all lines. On the other hand, if top-right and bottom-left lines appeared closer and the others looked farther at the same time, it would indicate that the stereo effect arose locally. The line orientation was 30 deg in a counter-clockwise direction from the horizontal. Observers viewed the figures in an anaglyph version of the figures and verbally reported their depth impression.

Twenty four people (who attended the annual meeting of the Association for Research in Vision and Ophthalmology, 2001) observed the stereo figures. Eighteen observers answered that top-right and bottom-left lines were closer and the others were farther. Three observers answered that top-right and bottom-left lines looked closer than the cross and the other lines, but that they were not sure whether the other lines looked farther than the cross or not. No one reported that all the lines in the four patches were at the same depth. Although the perceived depth in each patch tended to indicate its sign in accordance with the vergence hypothesis, the assumed vertical shift directions were determined independently in each quadrant, i.e., the effect was a local phenomenon.

The second stereogram consisted of lines and dots with the same disparity configuration as the first one, as shown in Fig. 3b. The only difference between the first and the second stereogram was the line orientation. The line orientation was 30 deg in a clockwise direction from the horizontal for the top-left and bottom-right patches or in a counter-clockwise direction for the top-right and bottom-left patches. In the second stereogram, 21 out of 24 observers reported the "all-closer" perception. The results again showed that the perceived depth in each quadrant tended to indicate its sign in accordance with the vergence hypothesis. However, if the effect was caused by a global vertical shift, the signs of the perceived depth should not have been the same because the line orientations were opposite between the quadrants. It seems, therefore, that the present stereo effect is determined in local regions in the visual field at the same time.

Some reasons why the effect could not be seen by some observers may be the anaglyph method, i.e., binocular rivalry, low contrast and cross talk between the two eye images. It is also possible that the vertical disparity was larger than the fusion limit at the viewing distance where the observer stood.

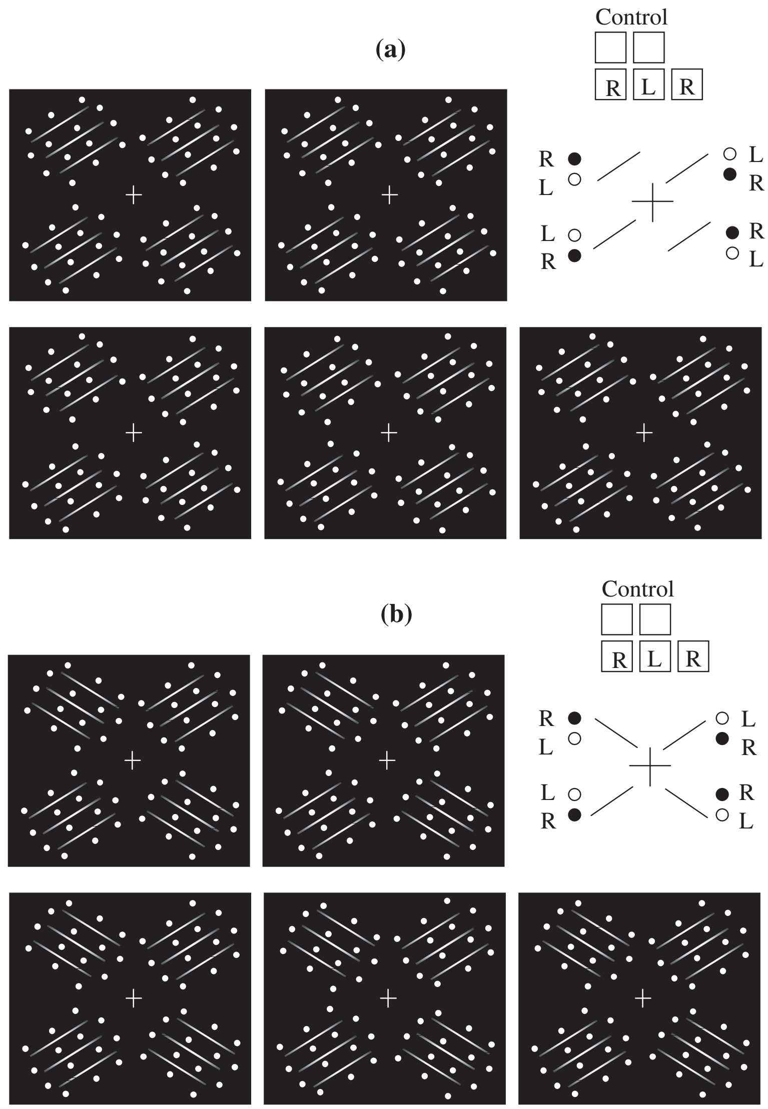

Fig. 3. The free-view versions of the demonstration figures. These figures were originally presented with the anaglyph method at ARVO 2001. When one fuses them, (a) upper-right and bottom-left line groups tend to look closer and other line groups tend to look farther, and (b) all the line groups tend to look closer.

It is important to note that cyclovergence also could not have produced the present effect. For example, if the right-eye image in Fig. 3b rotated around the fixation in a clockwise direction relative to the left-eye image, an uncrossed disparity arose for oblique lines in the top-right and top-left patches, while crossed disparity arose for those in the bottom-right and bottom-left quadrants. This induced disparity would not be compensated for by the human stereo system (van Ee & van Dam, 2003). Therefore, cyclovergence would have produced opposite depth signs between the top and bottom quadrants. For the same reason, cyclovergence would also have produced an opposite depth between the lines in the top-right and bottom-left quadrants in Fig. 3a. Clearly these predications are incorrect.

It is also noteworthy that the majority of the observers reported an opposite depth for top-left and bottom-right lines between the first and second stereograms (Fig. 3a and b), even though the whole disparity configuration was the same for the two stereograms. The only difference was the line orientation. Therefore, combinations of the signs of the vertical dot disparity and the line orientations, not the vertical disparity sign itself, determined the perceived depth sign. Although this combination effect can be expected from the vergence hypothesis in Fig. 2, the effect seems to arise locally and in parallel. It did not originate from eye-movements that produced a global shift or rotation of the retinal images.

3. Experiment 1

A brief presentation method was used in the experiment to investigate whether the illusion arose even under a condition where eye-movements could not occur. Experiment 1 examined the existence of the depth effect qualitatively, that is, whether or not the perceived depth sign was varied with the combination of line orientations and signs of the vertical dot disparity as noted above. Perceived depth positions of oblique lines without a disparity were tested, by varying the line orientation and the sign of vertical dot disparity (*dot-disparity condition*). It was predicted from the Demonstration noted above that the perceived relative depth position of the lines (closer or farther than the fixation cross) would depend on the combination of line orientations and signs of vertical dot disparity. As a control, there was a *line-disparity condition*, consisting of lines with a horizontal disparity (crossed or uncrossed) and dots without a disparity.

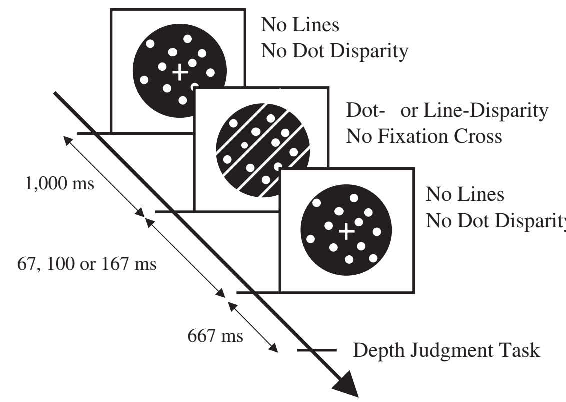

Fig. 4. A sample trial sequence in Experiment 1. See details in Section 3.1.

3.1. Method

3.1.1. Subjects

Two observers participated. One of them was the author. They were highly experienced in depth judgment tasks.

3.1.2. Apparatus and stimuli

Stimulus displays were created by a computer (SHARP, PC-PJ-X3) and displayed on a CRT monitor (EIZO, Flex Scan T561). The display screen was 1024 pixels wide × 768 pixels high. All the stimuli were displayed within a circular window for each eye, whose diameter was 11.3 deg in visual angle. The stimuli consisted of oblique lines and sparse dynamic random dots. The luminance of the lines, dots and region outside the circular window was 10 cd m^{-2} and the background luminance (inside the window) was 0 cd m^{-2}. Oblique lines were plotted with a horizontal interval of 1.8 deg. The end points of the lines were ambiguous. Since the luminance of the lines and that of the region outside the window were the same, there was no discontinuation of the lines at the edge of the window. The number of dots was 200 and their positions were randomly refreshed at 30 times/sec. The size of a dot was 3.4 arcmin horizontally and vertically. Subjects viewed the display stereoscopically using a prism stereoscope.

3.1.3. Procedure

The experimental trial sequence in the first experiment was as follows (see also Fig. 4); first, dynamic dots without a binocular disparity and a fixation cross were presented for 1000 ms within a circular window whose edge had no disparity. Second, under *dot-disparity conditions*, oblique lines without disparity and dynamic dots with vertical disparity were presented for 67, 100 or 167 ms without the cross. The dots had a vertical disparity of 3.4 arcmin in a positive or negative direction. Under *line-disparity conditions*, lines with a horizontal disparity (3.4 arcmin in a crossed or uncrossed direction) and dynamic dots without a disparity were presented. The line orientation was 45 deg or 135 deg from the horizontal, i.e., either top-right to bottom-left or top-left to bottom-right orientation, for both disparity conditions. The two conditions produced similar depth perception as shown in Fig. 1 and were difficult for subjects to distinguish from each other. The third part was the same as the first part of the stimulus presentation, lasting 667 ms. There was no time interval between them. Subjects responded whether the lines were seen at a closer or farther depth position, compared with the cross. If vertical disparity of the dots had no effect on perceived depth of the lines, the percentage of "closer" judgments under dot-disparity conditions would be around 50. Under each duration condition, trials under other combinations of conditions were run in a random order. In total, 60 trials for each combined condition were given to each subject.

3.2. Results

The results are shown in Fig. 5. Although there was no retinal disparity for the line images under *dot-disparity conditions*, their perceived depth positions systematically changed, depending on the combination of line orientations and vertical disparity signs as shown in the above described demonstration. This trend is still clear under the 67 ms-duration condition. On the other hand, under *line-disparity conditions*, only the horizontal disparity sign determined the perceived depth position, irrespective of the line orientation. From a qualitative point of view, the depth effect seems to clearly exist even under conditions of brief presentation.

4. Experiment 2

Experiment 1 qualitatively showed the existence of the depth effect. However, the results only reflected an

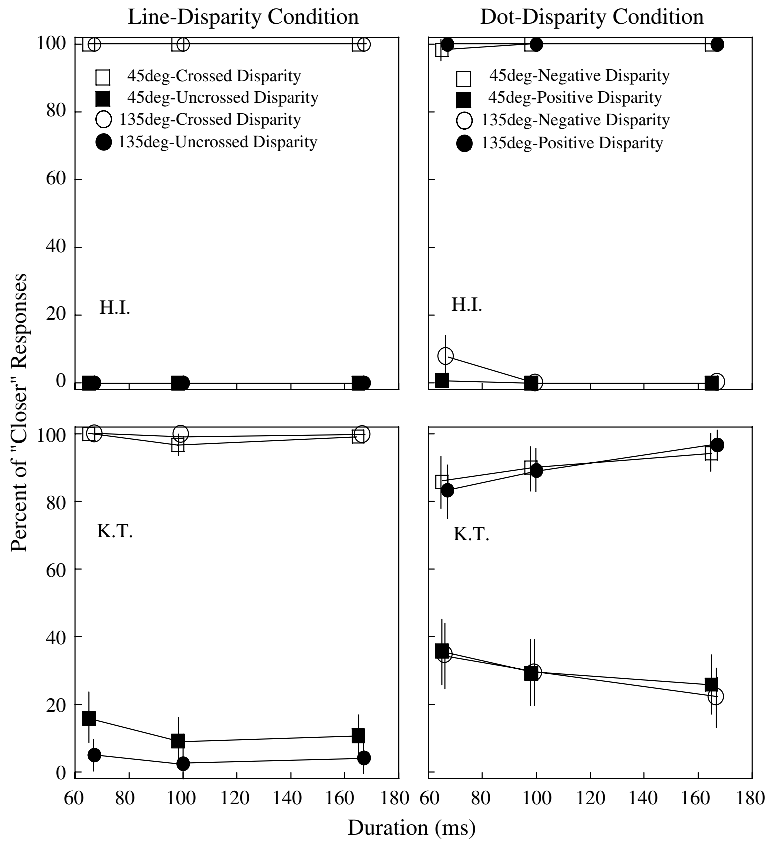

Fig. 5. Percent of "closer" responses in Experiment 1. When lines had real crossed or uncrossed disparity, the perceived depth position depended on the disparity direction irrespective of line orientation. When lines had no disparity and dots had a vertical disparity, the perceived depth of the lines depended on the combination of a line orientation and a vertical-disparity direction. The effect of vertical dot disparity on perceived line depth seems smaller than that of the real horizontal line disparity for T.K., but robustly exists even under the 67 ms duration condition. Vertical lines in the figure indicate 95% confidence intervals.

aspect of the depth-order perception by the effect. In addition, because the acquired results showed saturation even under the 67 ms condition, the effect of presentation durations was not clearly shown. The purpose of Experiment 2 was to quantitatively confirm the existence of the depth effect under those conditions. Experiment 2 measured the amount of perceived depth induced by vertical dot disparity when the lines appeared in front of the fixation plane, comparing it with the perceived depth from crossed horizontal line disparity. Both depth impressions were quite similar in quality as noted above.

4.1. Method

The method of constant stimuli was used. A sample trial sequence (shown in Fig. 6) in the second experiment was as follows. First, dots without disparity were presented for 1000 ms with a fixation cross. Then, a dot-disparity display, i.e., top-right to bottom-left 45-deg oblique lines without a disparity and dots with a vertical disparity (10.2 arcmin), was presented for 67, 100, 133 or 167 ms as a "test" stimulus. After an interval (the cross and dots without disparity were presented for 667 ms), a

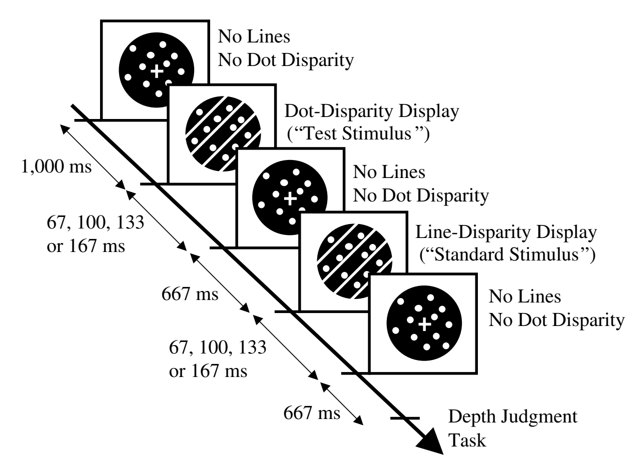

Fig. 6. A sample trial sequence in Experiment 2. See details in Section 4.1.

line-disparity display, as a "standard stimulus", was presented for the same duration as the dot-disparity display. In the line-disparity display, oblique lines had a crossed horizontal disparity (0, 1.7, 3.4, 5.1, 6.8, 8.5 or 10.2 arcmin), while the dots had no disparity. After this, the cross and dots without disparity were presented again (667 ms). The order of dot- and line-disparity displays was at random. The subjects judged whether the second presented stimulus was closer or farther than the first one. Under each duration condition, trials with other combinations of conditions were run in a random order. In total, 50 trials were given for each combination of conditions.

4.2. Results and discussion

Fig. 7 shows the psychometric functions obtained from the two subjects. The percentages of "test closer" responses were fitted with logistic functions ($R^2 =$ 0.988–0.998) to acquire horizontal-disparity values of "standard" stimuli when "closer" responses were 50%, indicating subjective equality between the depth from the vertical dot disparity and the depth from the horizontal line disparity. As shown in Fig. 7, the perceived depth from the vertical dot disparity, measured as a matched horizontal line disparity, slightly increased when the stimulus duration increased. However, even under the 67 ms (i.e., the shortest) duration condition, the depth effect was almost as convincing as that under the other duration conditions from a quantitative point of view.

Both Experiments 1 and 2 show that eye movements are not necessary to cause the effect. It is also shown that the effect includes not only a depth-order illusion but a measurable depth quantity. The existence of the effect under the brief presentation conditions suggests that the effect originates at a very early stage of stereo processing.

5. Experiment 3

Through the demonstration and the two experiments, the vergence hypothesis was rejected. However, the results show that the sign of the perceived depth of the effect was locally consistent with a prediction from the vergence hypothesis. As a working hypothesis, now I assume that the visual system has a function which locally compensates for the vertical misalignment of the both-eye images just like vertical vergence (this is called the shift-and-match hypothesis). It is also possible to consider this hypothetical shift as a result of vertical disparity contrast between that of the dots and lines.

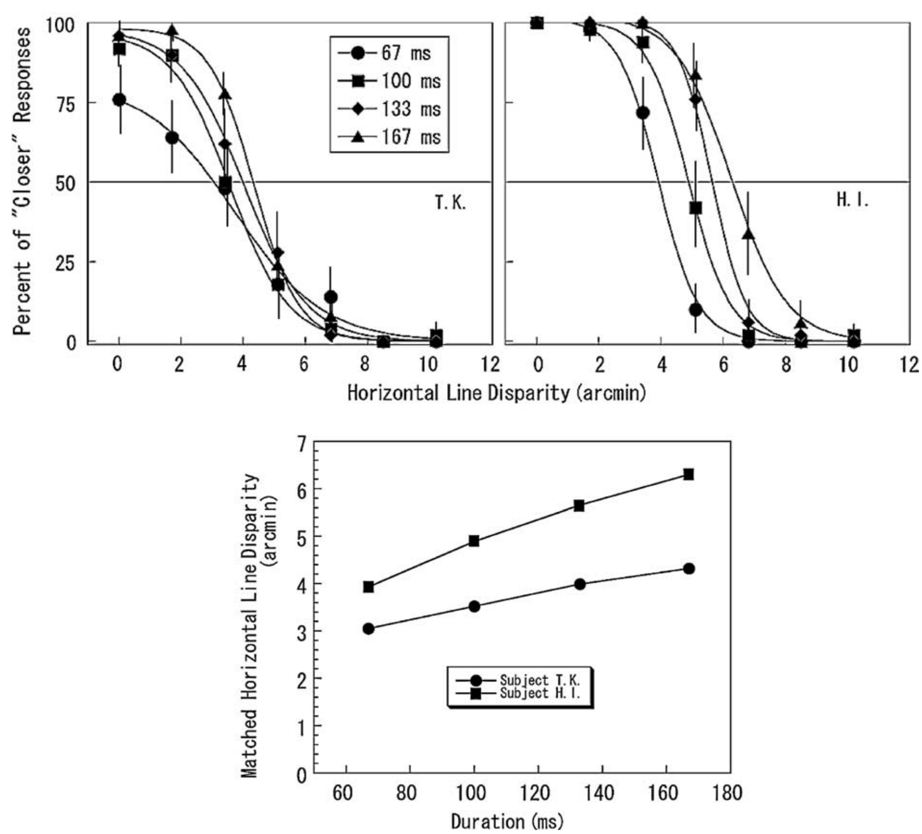

Fig. 7. Results from Experiment 2. When the horizontal line disparity in a "standard" stimulus was small, the percentages of "test-closer" responses were high. The amount of horizontal line disparity matched with the vertical dot disparity (10.2 arcmin) was determined at 50% of "test-closer" responses through fitting of logistic functions. As presentation duration increased, the perceived depth slightly increased. However, as in Fig. 5, the effect is still clear even under the 67 ms duration conditions. Vertical lines in the figure indicate 95% confidence intervals.

Compared to the vertical dot disparity, the lines should have the relative vertical disparity in the opposite sign.

Here I measure two more characteristics of the stereo effect, that concern the shift-and-match hypothesis. In the present experiment, I investigate an effect of line orientations. In Experiment 4, additivity between horizontal line disparity and the hypothetically induced disparity is tested.

van Ee and Schor (2000) showed that matching of disparate oblique lines would occur in the oblique direction, i.e., somewhere between the horizontal and a nearest neighbor direction. According to Fig. 2, if the induced vertical disparity were constant, more horizontal lines would get more horizontal disparity components in horizontal matching. In 45 deg line orientation, the horizontal disparity component should be equal to a vertical shift in its amount when the matching direction is horizontal. On the other hand, nearest neighbor matching predicts that the induced horizontal component would be at a maximum when the line orientation is 45 deg from the horizontal. When the line orientation is 45 deg, the amount of the induced horizontal disparity component in the nearest neighbor matching is estimated at a half of the amount of the induced vertical line disparity. Both oblique lines in 30 deg and 60 deg orientations would have 87% of the maximum horizontal disparity component.

As shown in Fig. 7, the results from Experiment 2 showed that the matched horizontal disparity under each condition was not equal to the presented vertical disparity of the dots (10.2 arcmin) but around a half of that. This may indicate that the matching direction after a vertical shift was around the nearest-match direction. However, it is possible that the amount of the vertical shift was a half of the presented vertical disparity while the matching direction was horizontal. In addition, the matched horizontal disparity of the standard stimuli assumed that the matching direction in the standard stimuli was horizontal, even though their orientation was 45 deg from the horizontal. If the matching direction in the standard stimuli had been oblique, the amount of actually perceived depth of the test stimuli would have been less than that imagined from the described horizontal disparity values. To investigate the matching direction of hypothetically shifted lines, perceived depth was measured by varying the line orientation. The stan-

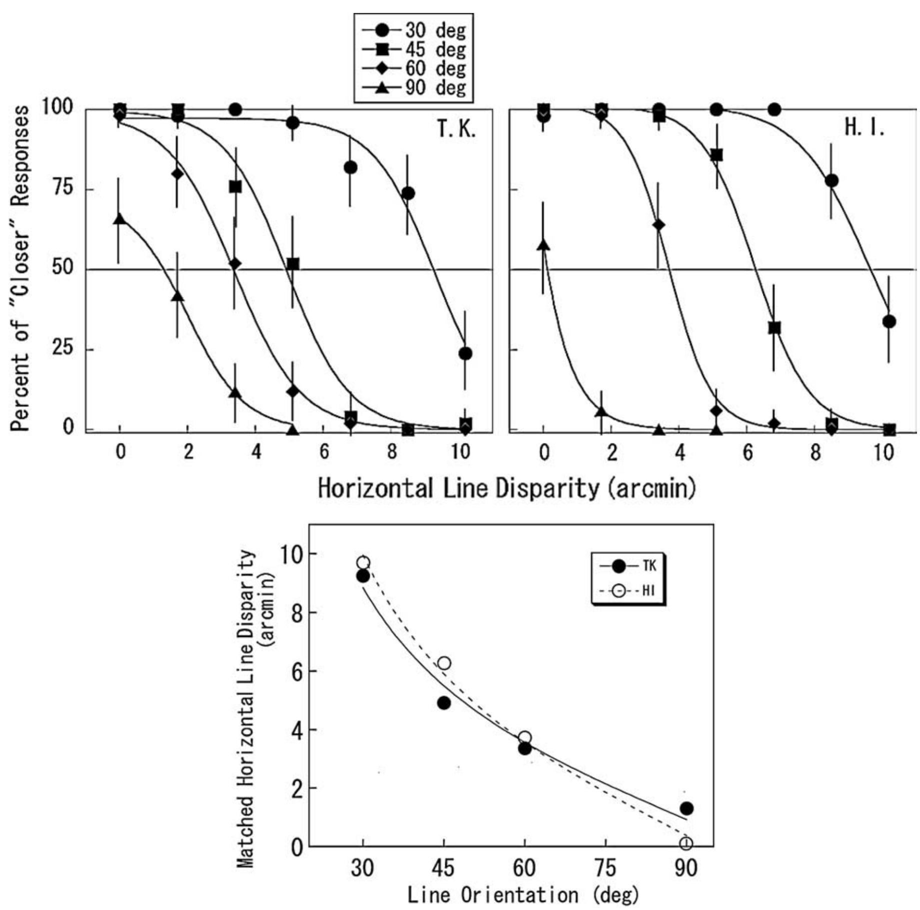

Fig. 8. Results from Experiment 3. As the line orientation got more horizontal, the matched horizontal disparity became larger. A 1/tangent function (curves in the figure) fits the data well. Vertical lines did not show the depth effect. Vertical lines in the figure indicate 95% confidence intervals.

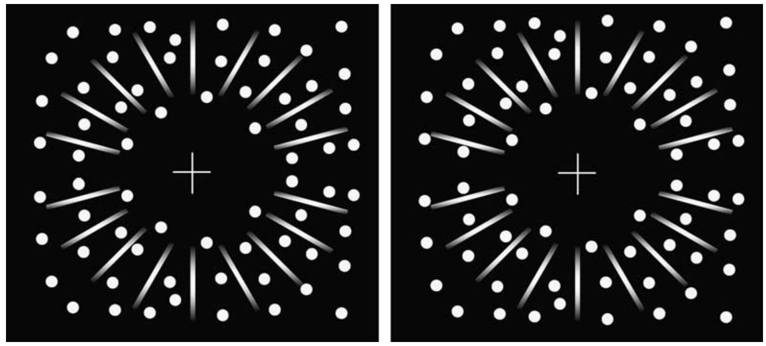

Fig. 9. The orientation effect of the oblique lines. The line orientation in the figure is 15, 30, 45, 60 or 90 deg in a clockwise or counter clockwise direction from the horizontal. The stereogram is available for both a crossed-eye and an uncrossed-eye (parallel-eye) method. When fused with a crossed-eye method, lines in the left side may be seen farther in depth and in the right side, closer in depth. When fused with an uncrossed-eye method, the opposite depth may be perceived. The lines do not have any disparity. The dots in the upper (lower) field have a negative (positive) vertical disparity with a crossed-eye method.

dard stimuli were always vertical, so that the horizontal disparity of the standard stimuli could be unambiguously defined.

5.1. Method

Experiment 3 measured the effect of line orientations on perceived depth, through the same procedure as used in the second experiment. The test lines were varied in orientations (30, 45, 60 or 90 deg from the horizontal). The duration was 167 ms. The subjects, apparatus, and experimental procedure were the same as in the second experiment. The standard lines were always vertical as noted above.

5.2. Results

The results are shown in Fig. 8. Logistic functions well fitted the data from each orientation condition for each subject ($R^2 = 0.969–0.997$). It is clear that the depth impression caused by constant vertical dot disparity monotonically increased as the line orientation became more horizontal. Fig. 8 shows the matched horizontal disparity as a function of the line orientation. The data well fit a 1/tangent function. The depth effect under the 30 deg orientation condition was much larger than that under the 45 deg orientation condition. This result supports horizontal matching rather than nearest neighbor matching. When lines in the test stimulus were vertical, little effect was found. This can be seen in Fig. 9.

6. Experiment 4

Here I examined whether or not the depth from vertical dot disparity and the depth from horizontal line disparity were additive (or subtractive), using the same procedure as in Experiment 1. The additivity can be easily imagined from Fig. 2. under the vergence hypothesis. However, if the vergence hypothesis and the shift-and-match hypothesis worked in a similar way, the latter would also show the additivity.

6.1. Method

The horizontal line disparity was 3.4, 1.7 or 0 arcmin in an uncrossed direction. Horizontal line disparity in an uncrossed direction caused a "far" impression when there was no vertical dot disparity. Vertical dot disparity also varied from 3.4 arcmin in the positive direction to 10.4 arcmin in the negative direction in 1.7 arcmin steps. Subjects responded the perceived depth position with the same method as in Experiment 1. The line orientation was fixed at 45 deg.

6.2. Results

Fig. 10 shows the results. Logistic functions well fitted the data from each horizontal line disparity condition for each subject ($R^2 = 0.975–1.000$). The parallel horizontal shift of the acquired data curves, according with the horizontal line disparity, indicates that both depth effects are additive. When horizontal line disparity was zero, the sign of perceived depth depended on the sign of the vertical dot disparity. When horizontal line disparity was 3.4 or 1.7 arcmin in an uncrossed direction with zero vertical dot disparity, the lines were seen farther than the cross in almost all trials. However, when superimposed vertical dot disparity was large in a negative direction, lines were seen as closer than the cross, i.e., the depth effect from vertical dot disparity overcame depth from the horizontal line disparity.

A possible explanation based on the shift-and-match hypothesis is that when the vertical line shift is greater than the uncrossed horizontal line disparity, the line's positional order reverses, resulting in the production of crossed horizontal line disparity.

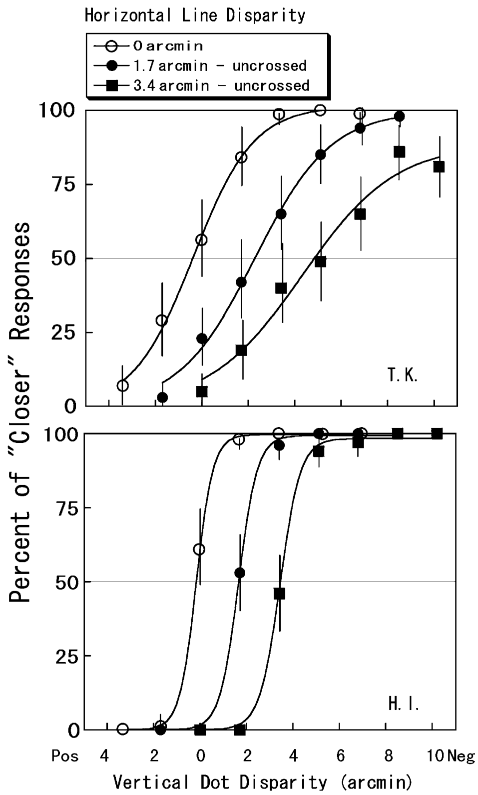

Fig. 10. Results from Experiment 4. The additivity between horizontal line disparity and the depth effect by vertical dot disparity is shown. Oblique lines even with uncrossed horizontal disparity (1.7 and 3.4 arcmin) appeared closer in depth when the overlaid vertical dot disparity was large. Vertical lines in the figure indicate 95% confidence intervals.

7. General discussion

Through the demonstration and the experiments, it was shown that oblique lines without retinal disparity are seen in depth when dots are overlaid with vertical disparity. This stereo illusion arises even when vertical vergence or cyclovergence does not occur, i.e., under parallel or brief stimulus presentation conditions.

The present experiments used presentation durations from 67 to 167 ms, including durations below a latency of vertical vergence (Duwaer & van den Brink, 1981; Howard, Allison, & Zacher, 1997; Kertesz, 1981; Nielsen & Poggio, 1984; Stevenson & Schor, 1997; Westheimer & Mitchell, 1956). As far as I know the shortest latency of vergence eye movement ever reported is about 80 ms (Busettini, Fitzgibbon, & Miles, 2001). Since a 67 ms presentation may be sufficiently brief to prevent vertical vergence, it seems difficult to attribute the experimental results to it.

Assuming that our brain could shift the images vertically to cancel or compensate for vertical disparity without vertical vergence, the shift-and-match hypothesis could explain the results from all the experiments. Since vertical vergence is usually based on the detected vertical disparity and occurs to horizontally align images to be matched, it is possible that detecting vertical disparity precedes horizontal matching. However, an image shift mechanism without vertical vergence is not known at present.

Alternatively, it is possible that the illusory depth of the lines is due to modifying a stereo matching direction of the lines along the oblique direction, even though the retinal images for both eyes are completely the same (stereo-capture hypothesis, see Fig. 11). The stereo matching direction between the oblique lines with disparity is ambiguous by nature, known as the aperture problem in stereopsis (Ito, 2003; Morgan & Castet, 1997; van Ee & Schor, 2000). In the case of lines without disparity, the matching points are ambiguous along the lines. When the stereo system fuses vertically misaligned images (i.e., dots) within the fusion limit (Duwaer & van den Brink, 1981; Stevenson & Schor, 1997), their neighbors (i.e., lines) may be expected to have a vertical disparity in the same way. That is, the visual system may favor vertically shifted matching points also for the lines to keep the smooth vertical disparity distribution. Detection of vertical disparity may prompt and reinforce the same vertical disparity detection in the neighbors. It is possible that matching points of oblique lines are modified to adjust the vertical disparity with the surroundings with a sacrifice of producing a new horizontal disparity component. This is considered as a kind of stereo capture (Kham & Blake, 2000; Ramachandran & Cavanagh, 1985) in vertical disparity. This will effectively shift the matching points for the lines along themselves, resulting in induction of a new effective disparity in the oblique direction, which could pro-

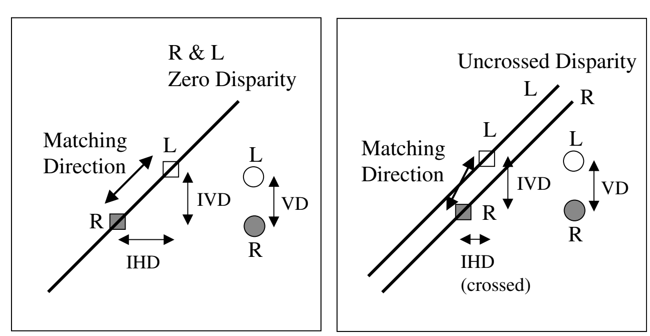

Fig. 11. The stereo-capture hypothesis for the illusory depth. The stereo system will modify the matching points along the oblique lines to match the surrounding vertical disparity of the dots. The oblique matching along the line induces virtual oblique disparity that includes induced vertical and horizontal disparity components (IVD and IHD). The right panel shows how the perceived depth sign of oblique lines with uncrossed disparity could be reversed by the negative vertical dot disparity (as in Experiment 4). Note that the IHD is a crossed horizontal disparity component, even though the horizontal line disparity is originally uncrossed. The matching direction in the right panel does not lie between the horizontal and the nearest neighbor directions.

duce a depth impression by the effective horizontal-disparity components. This hypothesis may explain the results shown in Demonstration and Experiments 1 and 2. This explanation can also explain the effect of the line orientation shown in Experiment 3 and perceived depth additivity shown in Experiment 4 (see Fig. 11). Additionally, this explanation does not assume the existence of new brain mechanisms. It only needs an extension of the aperture problem in stereopsis to zero disparity oblique lines and an extension of stereo capture to a vertical dimension.

The pooling of vertical disparity (Kaneko & Howard, 1997; Stenton, Frisby, & Mayhew, 1984) seems to be a relevant concept of processing in terms of smoothing the vertical disparity distribution. As for the horizontal disparity, the visual system directly utilizes the local irregularity for precise binocular depth perception although vertical disparity could also arise irregularly (e.g., in partially occluded surfaces Farell, 1998).This may be the reason why horizontally disparate dots do not capture the horizontal disparity component of oblique lines (see Fig. 1), whereas vertically disparate dots do.

Unfortunately, the present data do not show which strategy is more plausible, the shift-and-match hypothesis or the stereo-capture hypothesis. The key to decide between the two possibilities may be the vertical disparity sign of the lines. The vertical disparity sign is the same between the dots and lines in the stereo-capture hypothesis, whereas the shift-and-match explanation hypothesized the opposite vertical disparity signs between them. However, as we can not tell the vertical disparity sign of the lines, the two explanations are not distinguishable from the results here. Research with a new method seems necessary to solve the matter.

One may argue that the present effect is a depth contrast between perceived depth positions of the dots and the lines. The dots could be perceived in depth, e.g., because of the ''induced effect'' (Ogle, 1938, 1950). The relative depth between the dots and the lines could be attributed to the depth of the lines. However, there are some reasons to deny the explanation. One is the line-orientation dependency of the present effect. The same vertically disparate dots could produce either a near or far depth impression of the lines depending on the line orientation. Another reason is that horizontally disparate dots cannot produce the depth effect on the lines although the dots are perceived in depth. It is difficult to explain the present effect from the point of perceived relative depth between the dots and the lines.

Finally, from a point of methodology, the present effect can be a useful (and simple) tool to investigate vertical-disparity processing in the visual system. Depth effects by vertical disparity are usually difficult to observe phenomenally. However, the present depth effect clearly indicates that even when there is not an explicit depth impression by vertical disparity (as in the dots in this paper), vertical disparity is actually measured, not just tolerated.

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